SOLAR ACTIVITY, THE QBO, AND TROPOSPHERIC RESPONSES

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Abstract. The suggestion that galactic cosmic rays (GCR) as modulated by the solar wind are the carriers of the component of solar variability that affects weather and climate has been discussed in the literature for 30 years, and there is now a considerable body of evidence that supports it. Variations of GCR occur with the 11 year solar cycle, matching the time scale of recent results for atmospheric variations, as modulated by the quasibiennial oscillation of equatorial stratospheric winds (the QBO). Variations in GCR occur on the time scale of centuries with a well defined peak in the coldest decade of the "little ice age". New evidence is presented on the meteorological responses to GCR variations on the time scale of a few days. These responses include changes in the vertical temperature profile in the troposphere and lower stratosphere in the two days following solar flare related high speed plasma streams and associated GCR decreases, and in decreases in Vorticity Area Index (VAI) following Forbush decreases of GCR. The occurrence of correlations of GCR and meteorological responses on all three time scales strengthens the hypothesis of GCR as carriers of solar variability to the lower atmosphere.

Both short and long term tropospheric responses are understandable as changes in the intensity of cyclonic storms initiated by mechanisms involving cloud microphysical and cloud electrification processes, due to changes in local ion production from changes in GCR fluxes and other high energy particles in the MeV to low GeV range. The nature of these mechanisms remains undetermined. The height distribution of the tropospheric response and the amount of energy involved and the rapidity of the time response suggest the release of latent heat could be involved. Changes in cloud albedo and absorptivity to infrared radiation are also plausible. Both the release of latent heat and changes in radiative transfer can account for the observed changes in vertical temperature profile, leading to changes in the intensity of cyclonic disturbances that are associated with changes in vorticity area index. Theoretical considerations link such changes to the observed latitudinal movement of the jet stream.

Possible stratospheric wind (particularly QBO) effects on the transport of HNO_3 and other constituents incorporated in cluster ions and possible condensation and freezing nuclei are considered as relevant to the long term variations. This is an abridged version of the full paper that is being published elswhere.

RESPONSE OF TROPOSPHERIC TEMPERATURE PROFILE TO HIGH SPEED PLASMA STREAMS

The atmospheric response to short term solar wind changes near the earth has been examined using the data source of Lindblad and Lundstedt (1981, 1983). From their list of High Speed Plasma Streams (HSPS), defined by an increase in solar wind speed between consecutive days of at least 80 km s^{-1}, a set of stronger events has been selected defined by $dV = (V_m - V_o) > 200$ km s^{-1}, where V_m is the maximum speed of the interplanetary plasma stream in the vicinity of the earth, and V_o is the smallest speed on the first day. Over the period Jan. 1966 through Feb. 1978 there were 55 such HSPS associated with solar flares, and 196 HSPS not associated with flares. The non-flare streams were mostly associated with coronal holes and were considerably more frequent on the declining phase of the solar cycle, in agreement with the well known preponderance of recurrent magnetic storms during this period. The distinction between the flare and non-flare related HSPS corresponds approximately to the distinction made by Burlaga et al. (1984) between transient shock associated flows and corotating streams. (Nevertheless shock associated flows can sometimes result from coronal mass ejections not associated with flares.) HSPS in general are associated with gradients in the solar wind velocity transverse to the 'garden hose' direction of the large scale magnetic field, whereas the flare related events also include strong gradients along the garden hose direction. A number of terrestrial effects are associated with HSPS events, including magnetic storm related X ray emissions; thermal, chemical and dynamical perturbations of the thermosphere, and penetration of fluctuating large scale electric and magnetic fields to the surface. For many of the flare related events there is in addition the reduction of the flux of GCR that penetrate to varying depths through the atmosphere (Forbush decreases), and for some the precipitation of particles in the MeV to GeV range at high latitudes. These effects of solar wind disturbances have been described for example by Akasofu and Chapman (1972, particularly ch. 7) and more recent reviews are those in the series of US National Reports to the IUGG. Thus there are a number of possible short term carriers of solar variability to the atmosphere, and a detailed analysis is required to identify at least one that has the appropriate time variations to cause the observed tropospheric responses.

It should be stressed that the rather extreme HSPS events selected according to the criterion $dV > 200\ km\ s^{-1}$ are relatively rare, only 4 or 5 of the flare related events per year on average, with a maximum occurrence (around solar maximum) of 10 per year. We study these as diagnostics; if short term but rare GCR changes unambiguously affect the troposphere then 11 year and longer term GCR changes may do so also. Of the 196 non flare events, 55 were selected to form a comparison set, with each as far as possible a match by being about the same dV and near to the time of a flare event. In Fig 1 from the top panel down we compare superposed epoch analyses of solar wind velocity (V) in the vicinity of the earth; solar wind magnetic field strength (B); GCR flux at the surface; and tropopause pressure, using the first day of increase of solar wind velocity as the key day (day 0). For the flare related events (solid curve) B increased by about 4nT on average, relative to the previous level of 5-6nT. The peak effect is on day 0. For the non flare events there is an increase over several days preceding day 0, and a drop of 3-4nT afterwards. The third panel shows that the average Forbush decrease in the GCR neutron count rate at Dourbes, Belgium was about 1% for the flare related events. The peak effect is on day +2, and the percentage effect at 5-20 km altitude would have been several times larger (Pomerantz and Duggal, 1974), since the main GCR flux at these heights is at lower energies that are more strongly affected by the interplanetary magnetic field than the higher energy flux that reaches the surface. In the case of the non-flare related events, the GCR change is smaller and of a different shape. This might be considered strange in view of the closeness of the V variations, and some similarities of the B variations in the two data sets. However, as noted earlier, a very important variation in V and B for modulating GCR fluxes is in the gradient along the garden hose direction, associated with shocks and produced by coronal mass ejections mainly associated with solar flares, that are not easily separable from transverse gradients in measurements by spacecraft near the earth. Another difference is that for corotating streams the magnetic field strength increases a day or two before it does for shock associated flows, relative to the increase in solar wind velocity (Burlaga et al., 1984).

The bottom panel shows the response to the HSPS in tropopause pressure measured by radiosondes above Berlin, from the data series Meteorologische Abhandlungen. There is about a 20 mb increase in tropopause pressure on day +2 that is more than two standard deviations above the mean. The response to the non flare-related HSPS is less than one

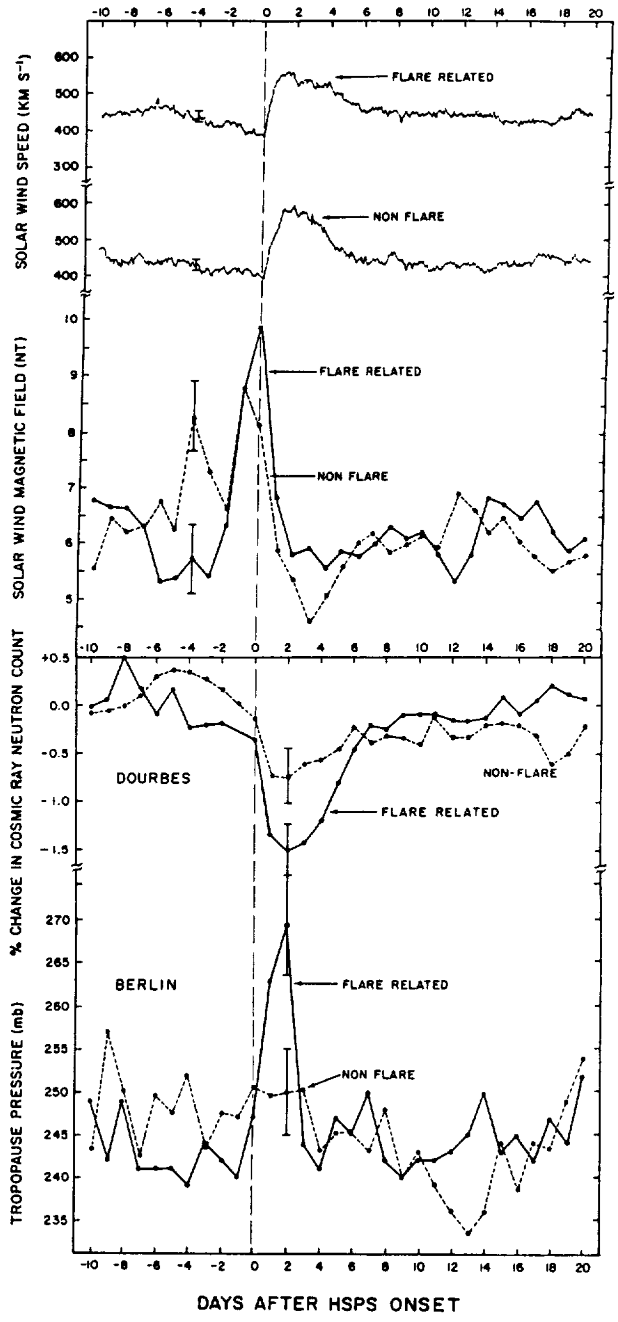

Fig. 1. Superposed epoch analysis for variability of solar-terrestrial parameters associated with 55 flare related and 55 non flare related high speed plasma streams in the solar wind, Jan. 1966 through Feb. 1978. Upper panel, solar wind speed and magnetic field; lower panel, surface neutron monitor countrate and tropopause pressure from European stations. Length of error bars is two standard deviations.

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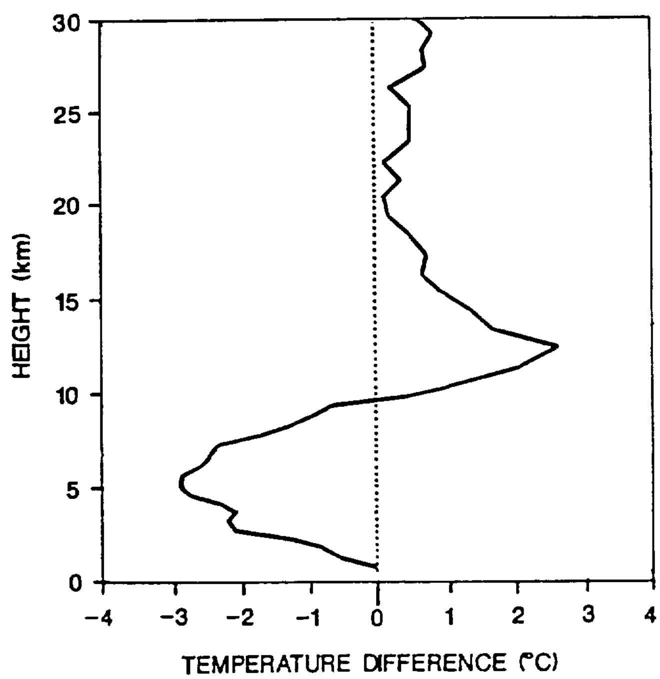

Fig. 2. Average atmospheric temperature change for the 55 flare associated events of Fig. 1, obtained by subtracting the profile for day -1 from the profile for day +2.

standadd deviation. The changes associated with flare related HSPS have not been found for lower speed streams than those selected here. The tropopause response also reveals itself as a change in the vertical temperature profile, and Figure 2 shows the average temperature change for the flare associated events computed as a function of height, obtained by subtracting the profile for day -1 from that of day +2. The response is in the form of a heating by 2-3^{o} C near the tropopause height (~12 km), and a cooling by about the same amount near 5 km, resulting in a decrease in tropopause height of about 0.7 km, that is equivalent to a pressure increase of about 20 mb. These tropopause height and temperature changes have been confirmed by direct examination of the measured parameters.

RESPONSE OF VAI TO FORBUSH DECREASES

In view of the tropospheric responses in Figs 1 and 2 being associated with Forbush decreases, it was decided to use specifically the days of onset of Forbush decreases as key days in a superposed epoch analysis of northern hemisphere VAI responses. A table of Forbush decreases greater than 3% observed by the Mt. Washington neutron monitor was used (NGDC 1985). The energy of the particles monitored lies primarily in the range 1-10 GeV. Actually, a more appropriate GCR flux to use in comparison with VAI variations would be that of about a factor of ten lower in energy, which is the main source of ionization and a source of chemical species in the lower stratosphere and troposphere. The neutron monitor data is used as a proxy for this lower energy GCR flux, which is supplemented at times by particles in the same energy range energised in the sun, the solar wind, and the magnetosphere.

The results of the superposed epoch analysis for 72 events from Nov. 1955 through April 1962, and for 106 events from May 1963 through Feb. 1982 are shown in Figs 3 and 4. The averaged variation of GCR observed with the Climax neutron monitor is shown for the same events. The VAI responses are further separated according to whether the events occurred in the winter months (Nov.-March) or the remainder of the year (April-Oct.), and according to whether they occurred in the QBO W or E phases. The results show that there is in general a reduction in the VAI associated with the reduction in GCR for both the 1955-62 and 1963-82 periods, and that this is deeper in the winter than in the non-winter, and that it is present for both QBO phases. A further subdivision of the winter data into E and W QBO phases (not shown) also resulted in the VAI reduction appearing about equally strongly in each phase. These events were not selected for steady solar wind or absence of sector boundaries or other Forbush decreases preceding or following the event within the epoch used in the analysis, as has been the case in previous VAI analyses, and some of the 'noise' in the VAI may be due to this.

PLAUSIBILITY OF GCR AS CARRIERS OF SOLAR VARIABILITY TO THE LOWER ATMOSPHERE

There are GCR variations that match the meterological and climate responses three different time scales. On the century time scale the decade of the 1690's, in the coldest part of the "little ice age" coincided with a peak in the ^{14}C and ^{10}Be production from GCR; the latter was 70% above levels before and after, from concentrations measured in Greenland ice cores (Attolini, et al.; 1988). There is an 11 year variation by about 50% in the GCR produced ionization at upper troposphere/lower stratosphere heights and an 11 year variation by a factor of about 10 in its day to day variability (Pomerantz and Duggal, 1974). The time variations of GCR and meterological variables in Figs. 1 to 4 show that GCR have appropriate time variations to be carriers of the short term (day to day) solar variability to the lower atmosphere. It is recognized that the presence of a correlation does not demonstrate by itself a physical connection. However the energetic particle hypothesis (low energy GCR and other particles of similar energy from the sun,

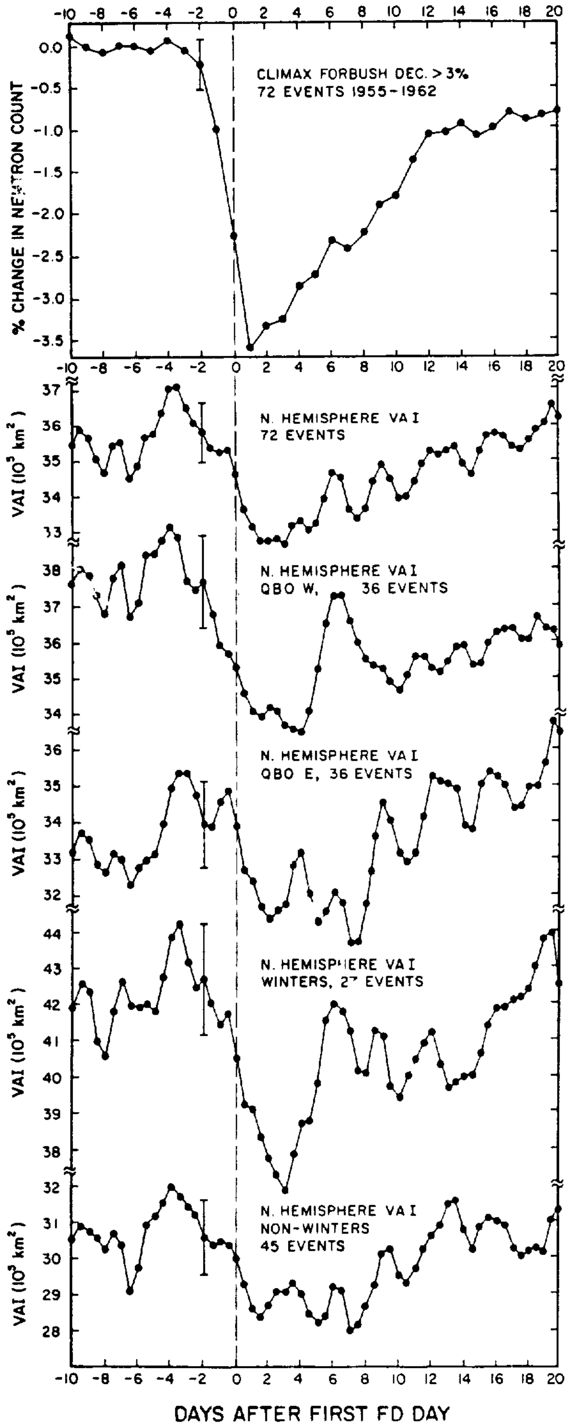

Fig. 3. Superposed epoch analysis of changes in hemispheric vorticity area index and Climax neutron monitor countrate associated with 72 Forbush decreases in Nov. 1955 through April 1962, with breakdown by QBO phase and winter-nonwinter intervals.

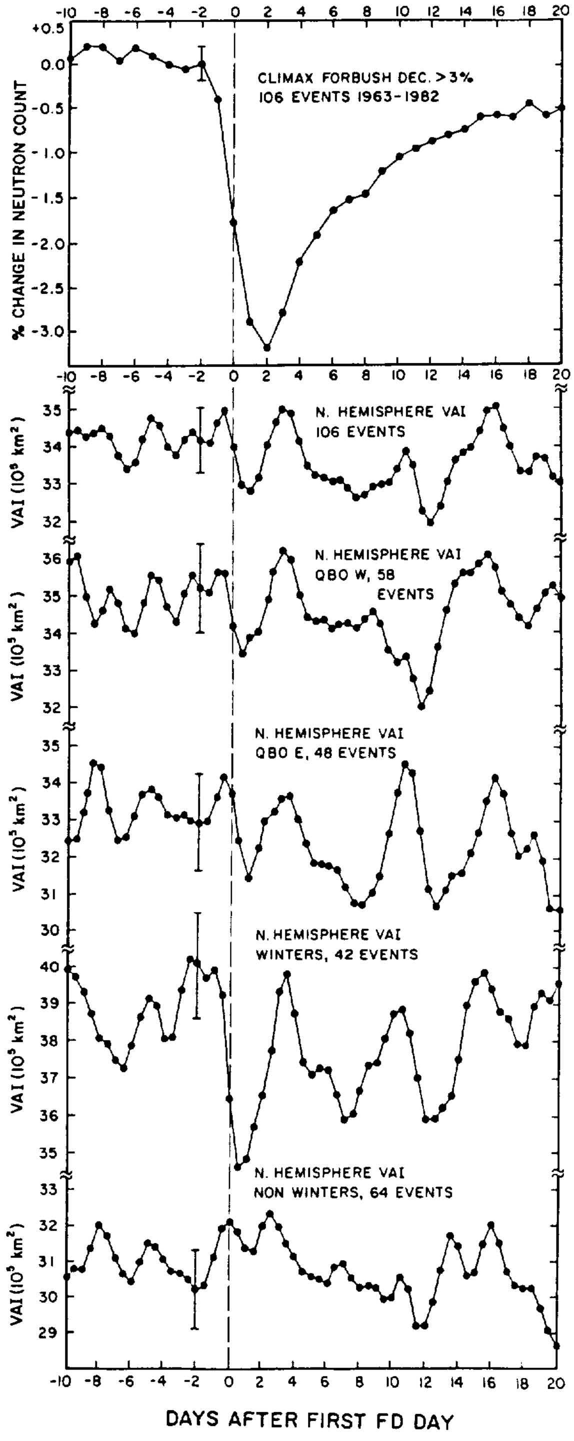

Fig. 4. As for Fig. 3 for 106 Forbush decreases in May 1963 through Feb. 1982.

interplanetary medium, and magnetosphere) seems the most promising one in terms of analyses made to date, and so we will continue to explore it.

The changes in height profile of Fig 2 occurred in the range 2-15 km, maximizing (in terms of energy involved) near 5 km or 500 mb. This is near where the greatest VAI response to sector boundary changes was found by Wilcox (1974) and not far from the 700mb level where Stolov and Shapiro (1974) found that large negative (cyclonic) centers developed in the 4 days following geomagnetic storms. This is the height range where in regions of uplift, associated especially with wintertime cyclonic disturbances, there is latent heat release occurring from conversion of water vapor to liquid and liquid to solid. Pauley and Smith (1988) showed that latent heat release exerted important direct and indirect influences on the development of a synoptic scale wave system containing an extratropical cyclone, particularly below 500mb, with latent heat release producing heating of up to $15^{\circ}C$ per day. In the same regions changes in the production of cirrus clouds would affect albedo to visible radiation and absorptivity to infrared. Thus changes in cloud microphysical processes associated with variations in GCR ionization could significantly affect the air temperature and dynamics of a cyclone. Only very small amounts of energy are required to initiate changes in these processes, if changes in condensation nuclei or ice nuclei are involved. If electric fields are involved in the cloud microphysics, then this is the height region where the conductivity is lowest and where only a small amount of energy in the form of a change in ion production has the greatest effect on the conductivity and electric field. The dominant source of ions in the troposphere and lower stratosphere above 1 to 2 km altitude is GCR.

An hypothesis linking the solar wind and cosmic ray changes on both short and long time scales to tropospheric and lower stratospheric changes is that: (a) an increase (decrease) in cosmic ray ion production in this region is reflected in changes in cloud microphysical and cloud electrification processes; so that (b) where there is supercooled liquid water or condensing vapor or evaporating droplets in regions such as cyclonic eddies in the jet stream, there is an increase (decrease) in the release of latent heat associated with the changes of state of water, and changes in cloud albedo and infrared absorptivity; that (c) affect the vertical temperature gradient; that in turn (d) increases (decreases) the intensity of the cyclonic eddies and thus increases (decreases) the vorticity area index. It is likely that: (e) there will be associated changes in wave activity that generate a divergence in the momentum flux in the general circulation; that (f) thereby produce latitudinal shifts in the mean latitude of the jet stream and in averages of storm track latitudes.

For Forbush decreases, a decrease in latent heat release in storms would occur with the above scenario, and this matches the observed reduction in temperature near 5 km as shown in Fig. 2. While changes in latent heat release would generally be associated with individual storms, this is not necessarily the case for changes in cloud albedo and absorbtivity. If these changes occur over a large region, say poleward of the jet stream, they could produce a change in temperature profile in that region that would affect the pressure gradient across the jet stream leading to a change in the average intensity or frequency of cyclonic eddies. There is an increase in the number of low pressure areas crossing 60° W meridian between latitudes 40° and 50° N, for the QBO W phase for minimum solar activity (Labitzke and van Loon, 1988), and this frequency change is associated with a downstream shift in the latitude of the jet stream and storm tracks in the eastern N Atlantic (Brown and John, 1979; Tinsley, 1988). This frequency change may be produced by a localised latent heat release in the storms, or by a distributed effect due to cloud and radiative changes over a large area, and in either case the association with the jet stream latitude shift can be understood theoretically if the increased frequency of lows at solar minimum (that corresponds to about one every 2-3 days, as compared to about one every 4-6 days at solar maximum) leads to a greater divergence of momentum flux, by greater generation of waves, including gravity waves, that propagate out of the region. As discussed, for example by Hoskins (1983, p 190-3), this will lead to a downstream poleward movement of the jet stream and storm tracks, in accordance with the observations. Also Pauley and Smith (1988) found that the effect of releases of latent heat in their simulated cyclonic disturbances was to intensify the storm and cause the downwind storm track to shift poleward. Both decreases in VAI associated with Forbush decreases, of which more occur at solar maximum, or VAI decreases associated with the lower general level of GCR flux at solar maximum, could account for the more equatorward storm tracks at that time.

In the stratosphere 27 day and longer term variations have been found that can be partially explained in terms of changes in the flux of solar ultraviolet radiation as the carrier (Keating et al., 1987; Brasseur et al., 1987). The energy involved in the stratospheric response is very small compared to that in the tropospheric response, and it is difficult to see how effects could propagate downwards and be amplified rapidly enough to account for tropospheric changes in the time scale of the HSPS and FD responses. On the contrary, it appears more likely that wave energy from tropospheric responses propagates upwards and towards the poles, and accounts for some of the unexplained stratospheric temperature variations.

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